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# OCULAR HALOES AND CORONAS*

BY

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## INTRODUCTION

FOR this paper to serve its purpose it is necessary that an account should be given of its origin and how it came to be written.

I am a meteorologist by profession and one of my early meteorological papers, entitled "On Coronas and Iridescent Clouds", was published in 1912. From that time onwards I have been particularly interested in the haloes and coronas seen on the clouds around the sun and moon and have made a close study of the physics of such phenomena. In January, 1950, in my 72nd year, I observed on a dark night that the street lights were surrounded by coloured rings. Thinking that these were of meteorological origin I was surprised not to be able to find anything in the state of the atmosphere to account for them. On subsequent nights the rings were still visible and as there could now be no possibility of a meteorological origin I consulted an ophthalmic surgeon. He found signs of mild congestive glaucoma and advised operations of basal iridectomies on both eyes. These operations were successfully performed in February and March and all traces of glaucoma disappeared. The coloured rings, however, continued to be seen.

By this time I was naturally very interested in the physics of the rings and having no acquaintance with ophthalmology I concluded that they were similar to the meteorological coronas with which I am so familiar. The latter are due to the small particles of water of which clouds are composed, and I jumped to the conclusion that my coronas were also caused by small particles either on the surface or within the eyes.

I soon found that the coloured rings I see are not part of a corona formed by particles, but a circular spectrum produced by the radial fibres of which the crystalline lens is built up acting as a circular optical grating. Although ophthalmologists have known this form of coloured rings, which they call the "lenticular halo", and the physics of its formation, since Druault described and explained it in 1897, I know of no reference to a circular optical grating producing a circular spectrum in any text-book of physics. I therefore continued my study of the exceptionally brilliant halo which I see. Chapter I of this paper contains a record of my study of the lenticular halo and gives a detailed account of the physics and optics of this interesting, if unimportant, phenomenon.

One dark morning in January, 1951, on looking out of a window shortly after waking, I saw a brilliant, unfamiliar corona around a near street lamp

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which completely swamped my lenticular halo. This time there could be no doubt that I was seeing a corona formed by particles similar to those seen on clouds; but I had no time to make any measurements before it disappeared. I did not see such a corona again until November, 1951, when I saw one around the flame of a match which I was holding in my hand, also shortly after waking. Connecting the corona with waking, I commenced what proved to be a long series of observations. For 5 months I looked for the corona each morning immediately on waking: it appeared for a few minutes on 86 out of 140 mornings and at no other time of the day. Each morning on which the corona was visible I carried out a series of observations which resulted in a great deal of information on the origin and physics of the corona and this forms the subject matter of Chapter II. This form of corona was first described by Descartes in 1637, in what must have been the first scientific description of a physiological corona. I therefore suggest that as ophthalmologists have no special name for this form of physiological corona they might adopt the name " Descartes corona".

I have already mentioned that the lenticular halo, the subject of Chapter I, is a circular spectrum produced by a circular optical grating. Now in a normal linear spectrum formed by a rectangular optical grating there is no light between the image of the source and the first-order spectrum; the space within my lenticular halo should therefore have been dark, but it was not. When I realized that there was no connexion between the coloured rings of the halo and the white light within it, it became clear that another origin had to be sought.

By questioning my friends I found that although they saw no coloured rings round a bright light they did see a glow around it, which agreed well with what I saw within my halo. I found that this glow seen by normal eyes is called the " ciliary corona " because of the large number of fine threads of light which radiate across it from the light in the centre. Chapter III is devoted to a description of the ciliary corona and the rays of light of which it is largely composed. I could find no explanation of how this glow is formed beyond "scattering of the light in the eye", but I give reasons to believe that it is a diffraction effect: namely, the aureole (the bright centre) of a corona formed by particles of a uniform size distributed at random within the eye.

Thus this paper deals with three major diffraction effects having their origin within the eye:

(*a*) the lenticular halo, due to a circular optical grating formed by the radial fibres at the periphery of the crystalline lens (Chapter I),

(*b*) the Descartes corona, due to particles on the anterior surface of the cornea (Chapter II),

(*c*) the ciliary corona with its rays, which I suggest is due to uniform particles within the eye, the exact position of which has not yet been determined (Chapter III).

I do not think that there is anything essentially new in (*a*) and (*b*); but so far as I know the ciliary corona and its bright rays have not previously been recognized as a diffraction effect. This study was not undertaken as a research; but as the duty of a physicist to make a full record of a physical phenomenon he is in a unique position to observe and investigate. If the work is found useful to ophthalmologists or physicists the credit must go to Mr. L. H. Savin who encouraged me to make the observations and gave me several opportunities to discuss them with himself and his colleagues; I should like to thank Dr. W. S. Stiles of the National Physics Laboratory for arranging the apparatus for me to see several effects which I could not see elsewhere and for his valuable advice; I wish also to thank Mr. E. F. Fincham of the Institute of Ophthalmology, London, who placed his experience of the optics of the eye, especially of the lenticular halo, at my disposal.

## Chapter I

## The Lenticular Halo

**General Description of What is Seen.**—When I observe a small source of light in an otherwise dark room there appears to be a series of coloured rings around it. Coloured rings of this nature are well known in physics and ophthalmology, there are several different kinds, each due to a different cause; as stated in the introduction we discuss three of these in this paper. In this chapter a description is given of the lenticular halo, the name given to coloured rings due to the radial fibres of which the crystalline lens of the eye is built up. Many people with normal eyes can see traces of these rings, especially when the pupil of the eye is dilated by an application of a mydriatic, but in my case the halo is so bright that I see it at night as a brilliant object around all bright lights, even in a well lighted room, and during the day around images of the sun reflected in polished surfaces. It is a striking object around the full moon, and I have seen it, but rather faintly, around a crescent moon only 4 days old.

In Fig. 1, lenticular haloes are shown diagrammatically around two similar electric street lamps, each about 25 ft high, the nearer, A, being approximately 75 ft away, and the other, B, about 100 yards away. A halo is seen around each light, but compared with the equal heights of the lamp posts the halo around B appears larger than the halo around A. This is because

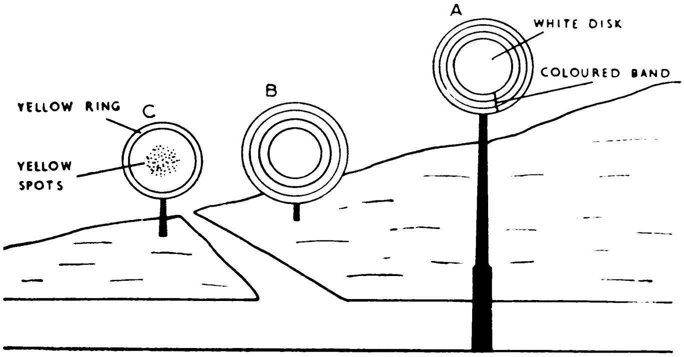



Fig. 1.—Coloured rings around street lamps. A and B, white light; C, yellow sodium light.

the haloes always subtend the same angle at the eye whatever the distance of the light around which they are centred. For this reason the halo seen around the flame of a match held at arm's length appears no larger than the length of the match stick; but it subtends the same angle as the large haloes seen around the street lamps.

The source of the light in the street lamps, shown at A and B in Fig. 1, is an electric filament which is too bright to be observed in detail. Immediately surrounding the blinding light of the filament there is a disc of light which shows no colours and decreases in brightness from the centre outwards. Concentric with the disc and in contact with it all round is the broad circular coloured band composing the lenticular halo itself. The halo is composed of coloured rings in the order of the spectrum colours, from violet near the disc to red on the outer border.

At first I thought that the central white disc and the surrounding coloured rings were all part of a corona similar to those seen on the clouds round the sun and moon, which consist of a bright white aureole at the centre surrounded by coloured rings. Further study however showed that this was not so, the white disc at the centre being no part of the surrounding coloured band and having quite a different origin. In this chapter we are dealing only with the latter.

In Fig. 1 it will be noticed that the upper part of the lamp posts is completely hidden by the halo, as though the halo were in front of the lamp post. When I hold a pencil at arm's length between the eye and the halo, it does not appear dark against the bright halo, but appears to go behind it. Similarly, if I look from a dark room through a window at a lamp outside, the halo appears to be within the room and completely hides the framework of the window spreading in front of the dark walls at each side.

This is not the case with coronas seen on clouds, for any obstacle between the cloud and the eye is seen silhouetted against both corona and cloud. The difference is explained by the fact that the light in one case is diffracted in the cloud beyond the obstacle, while in the other it is diffracted within the eye and swamps all other images on the retina.

**Detailed Description of the Lenticular Halo.**—The lenticular halo is not a homogeneous band of colour, but is built up of innumerable radial rays. An attempt has been made in Fig. 2 (overleaf) to represent the structure of the halo so far as it is possible in black and white. Of necessity the diagram is a negative, the dark streaks representing bright rays. The source of light is shown at the centre, surrounded by the disc of white light in which bright rays are depicted. As already stated, this white light between the source and the coloured rings has nothing to do with the halo. All that it is necessary to say about it here is that the rays in this disc are entirely separate from the rays of which the halo is composed. The rays in the halo are clear and sharp but very irregular; they vary in length and brightness and occasionally make appreciable angles with their neighbours. Each ray is a spectrum, all six colours of a spectrum being clearly seen on each. Generally the colours on each ray are at the same distances from the centre, thus

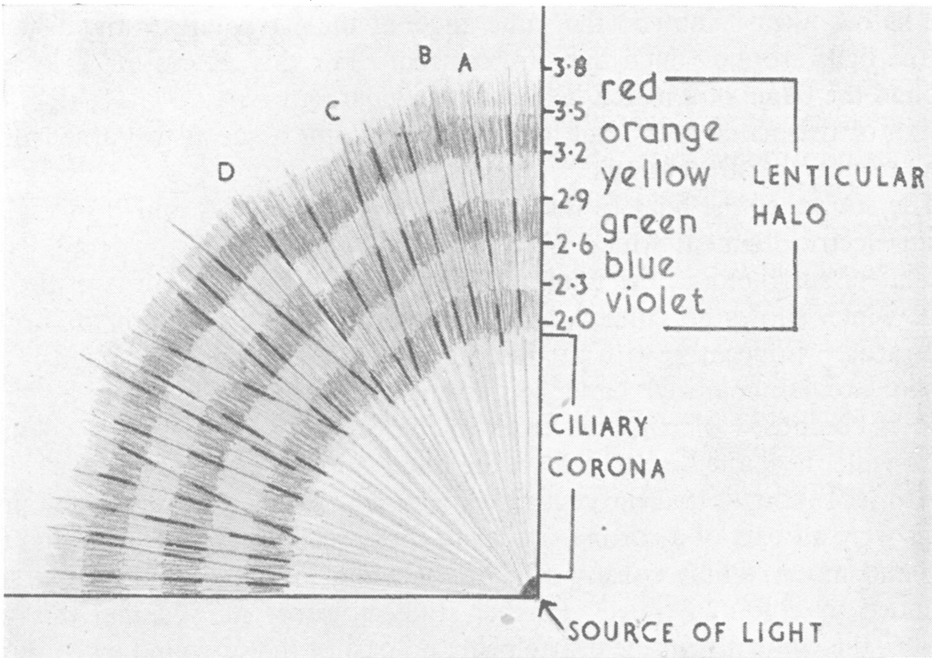



FIG. 2.—Details of coloured rings: white light.

giving rise to a series of concentric coloured rings which combine together to form the coloured band. In the diagram, alternate coloured rings have been indicated by thickening the strokes representing the rays, while the brighter rays are indicated by thickening the whole ray.

It will be noticed at once that the coloured band is not a perfect circle. The large irregularity near the middle of the quadrant occurs only in the halo seen by my left eye and is repeated in a corresponding position in the opposite quadrant. It appears as though a bundle of rays has been shortened, carrying the coloured parts inwards towards the centre. Examining the individual rays, it will be seen that the position of the colours along some of the rays are displaced, some inwards and some outwards, relatively to the general run of the colour rings. Also it will be noticed that the brighter rays extend beyond the general limit of the rays. The halo is not uniformly bright all round, some segments being appreciably brighter than others, giving rather a patchy appearance to the band as a whole.

Druault (1898) appears to have been the first to ascribe this halo to the fibres of which the crystalline lens of the eye is built acting as a circular optical grating. There is now no possible doubt that Druault's explanation is correct. A circular grating is not often met with in physics and I cannot find any such description in the text-book of physics available to me. I therefore propose to sketch the optics of a simple arrangement of a circular grating and a lens which produces a circular spectrum in all essentials similar to the lenticular halo.

**Optics of a Circular Grating.**—Fig. 3 shows a biconvex lens with its equatorial plane in the plane of the paper, the axis of the lens being the line through the centre perpendicular to the paper. An optical grating is shown etched on the outer zone of the lens, the lines of the grating being radial. The focal plane is parallel to the plane of the paper, but at the focal distance, *f*, beyond it. The focus of the lens is at the point *F* where the axis of the lens meets the focal plane. The source of light is on the axis above the plane of the paper; it is sufficiently small and sufficiently far away for the wave front of the light from it to reach the grating in the plane of the paper so that the phase of the wave is the same at all points on the grating. The lens may be considered to consist of two parts, first the central zone within the grating, and secondly the circular zone carrying the grating. With the only source of light on the axis, all the light which passes the central zone is collected at the focus, *F*, and the focal plane therefore receives no light through the central zone except at the focus.

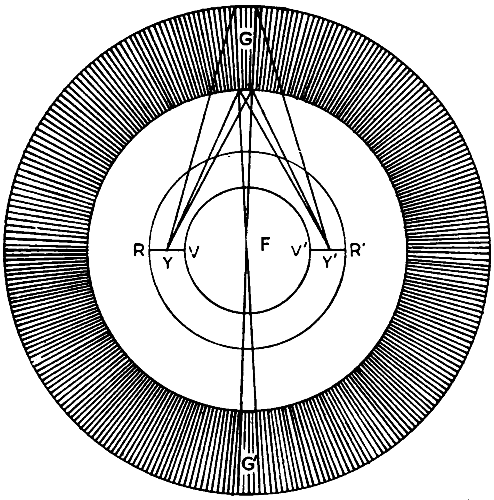



FIG. 3.—Circular grating and spectrum.

The path of the light which enters the lens through the grating can best be described by relating what happens to a beam of monochromatic light which passes through a conventional rectangular grating consisting of parallel lines engraved on a glass plate placed between a source of light and a lens. Before the grating is introduced, the lens simply forms an image of the source on the focal plane. When the grating is introduced, two more images appear, one on each side of the original image, the straight line on the focal plane joining all three images being at right angles to the lines on the grating. The distance between the central spot and the side images depends on the colour, so that when white light is used a spectrum is produced on each side of a white central spot. In this way the first order spectrum is produced; we shall not need to consider spectra of higher orders.

Returning now to our circular grating represented in Fig. 3, here again we have a grating placed between a source of light and a lens; but in this case the lines on the grating are not parallel. If, however, we consider a small segment of the circular grating between two radii near to one another, as depicted in *G* in Fig. 3, the lines in this segment are practically parallel and will act like a similar area on the rectangular grating we have already considered. Thus, when monochromatic light, say the yellow light of a sodium flame, from a source on the axis of the lens falls on *G*, it will produce three yellow images of the source on the focal plane. One will be at the main focus, *F*, where it combines with the light from the clear part of the lens, and two diffracted images at *Y* and *Y′* on a line *Y F Y′*, the diameter through *F* perpendicular to the lines of the grating in *G*. If red light is now substituted for the yellow light, red spots will be formed at *R* and *R′* on the same diameter, the distances *F R* and *F R′* being greater than *F Y* and *F Y′* because the wave-length of red light is greater than that of yellow light; similarly violet light produces spots at $V$ and $V'$. Thus white light passing through $G$ produces two line spectra, one between $V$ and $R$ and the other between $V'$ and $R'$, both on the diameter through $F$ perpendicular to the lines in $G$.

The next segment of the grating on the right of $G$ will produce two more spectra on the right of $R\ V$ and $R'\ V'$ respectively. When all such segments between $G$ and $G'$, that is the whole of the right-hand half of the grating, have been added, there will be spectra corresponding to $R\ V$ on every radius on the upper half of the band between $R\ V$ and $V'\ R'$, and similarly spectra corresponding to $V'\ R'$ on every radius in the lower part of the same band. Thus it needs only half the grating to produce a complete circular spectrum on the focal plane. The left-hand half of the grating exposed alone will also produce a complete circular spectrum. Thus when the whole grating is exposed two complete circular spectra are formed on the focal plane, but as they fall on one another they combine to form a single circular spectrum.

We are now in a position to apply this simple theory of the optics of a circular grating to the problem of the formation of the lenticular halo.

**Formation of the Lenticular Halo.**—The eye is a complex optical system, but for this discussion, if due care is used, it may well be represented by the simple lens and grating we have used in the above simplified theoretical discussion. The bi-convex lens, the optical grating, and the focal plane will then represent the compound lens of the eye, the radial fibres of the lens, and the retina respectively, more or less in their true relative positions.

At first it is difficult to form a mental image of the fibres in the crystalline lens which form the grating. This is because most of us who have learnt our optics from elementary text-books of physics think of an optical grating as composed of a series of parallel opaque lines drawn on a transparent surface with the lines generally of the same thickness as the transparent spaces between. Consequently when one is told that the lenticular halo is formed by fibres in the crystalline lens, the fibres are thought of as opaque threads in the transparent substance of the lens. The grating with opaque lines however is only one form of optical grating, and is used in elementary text-books because it lends itself to easy numerical calculations. The strict definition of a grating has been given by Schuster (1904):

> a grating is a surface having a periodic structure which impresses a periodic alteration of phase or intensity on a transmitted or reflected wave of light . . .

Thus a grating may be formed by laying fine straight glass fibres side by side and touching one another, the " periodic alteration of phase " being set up by the shape of the glass fibres. The fibres in the lens of the eye are of this nature; without being too technical, they may be described as long strips of transparent material, having a cross section of hexagonal

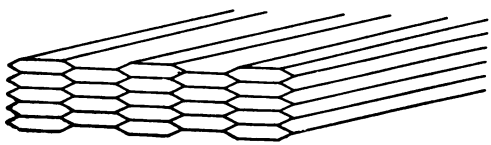


FIG. 4.—Lens fibres.

shape, but with two opposite sides of the hexagon much longer than the other, packed tightly together as in Fig. 4. A structure of this kind makes a very effective grating while being quite transparent.

The whole substance of the crystalline lens is composed of fibres of this nature; their diffractive effect is however limited to the periphery, where, on the whole, they are uniform in size and radial in direction, but there are local irregularities which we shall have to study later. The central part of the lens, although built up of similar fibres, shows no diffraction and therefore may be considered to be optically homogeneous.

The focal plane of the theoretical discussion corresponds to the retina in the eye. With a perfect circular grating on the crystalline lens there would be a perfect circular spectrum formed on the retina. When the eye " looks at " a point source of light at its own level, the axis of the eye is horizontal, the plane of the retina is vertical, and the light from the source is brought to a focus where the axis meets the retina. We have now on the vertical plane of the retina a physical point of white light surrounded by a physical band of rings of coloured light corresponding to the circular spectrum in Fig. 3. Converted into sensation, this produces the appearance of a halo with perfect rings of coloured light on a vertical plane surrounding the source of light. But the lenticular halo is not composed of perfect rings of coloured light; it is composed of coloured rays of unequal brightness and unequal length, and of rings of coloured light which are far from being perfect circles. We have now to study how the structure of the halo depends on the fibrous structure of the crystalline lens.

In the theoretical discussion, we found that the spectrum on the radius at $R\ V$ (Fig. 3), is due to the lines in the two small segments of the grating at $G$ and $G'$ combined, and that the spectra at the other positions are also due to the lines in similar small segments of the grating. Now the distance of any colour in a spectrum from the image of the source (the deviation) depends on the distance between corresponding points on adjacent lines in the grating (*i.e.*, in our case, on the distance between the centres of adjacent fibres). Hence when the colours on a ray in the halo are displaced towards the centre relatively to the general run of the rings, for example the ray at $A$ in Fig. 2, we know that the fibres which cause this ray are wider than the average fibre. Similarly if the colours on another ray are displaced away from the centre, as at $B$ in Fig. 2, we know that this is caused by fibres below the average in width. We shall later see how to determine where the fibres causing any ray are situated, but at present it is sufficient to know that the irregularities of the colour band indicate variations in the widths of the fibres in different positions on the outer zone of the crystalline lens. It is not certain why the rays vary so much in brightness; it is not likely to be due to the crowding of the fibres together, for that would involve reducing the width of the lines when all the brighter rays would have longer spectra which they have not; it is more likely to be due to bunches of fibres which are more uniform both in size and direction than usual, for example like a tress of hair which has been straightened by slight tension, the diffraction of such a bundle would be more perfect than of a less regular bunch of fibres and therefore brighter. At *C* there is a ray which is far from being radial; this must be due to a bunch of fibres being pulled out of place so that their direction is not truly radial. Between *D* and *C* the rings are abnormally disturbed, a large section being bodily displaced towards the centre, and this is repeated in the opposite quadrant. The natural explanation is that an appreciable section of the fibres in the left eye (there is no similar irregularity in the halo of the right eye) are abnormally wide, involving contracted spectra. It is interesting and instructive to locate the position of this abnormality in the fibres of the crystalline lens of the eye. In drawing Fig. 2, the source of light was supposed to be at the same height as the eye, hence the axis of the lens was horizontal and the plane of the retina and the apparent plane of the halo were in consequence both vertical. The halo reproduces the image on the retina; but we know that the image on the retina is inverted, *i.e.*, rotated through 180°, relatively to the object of which it is the image. Thus the top and left side of the halo correspond with the bottom and right side respectively of the image on the retina. Hence the image of the distortion in the top left-hand quadrant of the halo in Fig. 2 must be in the bottom right-hand quadrant of the image on the retina in Fig. 3. The rays in the image on the retina, however, are produced by fibres in the grating which are perpendicular to the rays, hence the rays in the bottom right-hand quadrant of Fig. 3 are produced by the fibres in both the top right-hand quadrant and the bottom left-hand quadrant of the grating. Thus the abnormal fibres may be in either of these two quadrants, but in which we cannot say without further data. We know, however, that if one half of the pupil is covered we still see a complete halo, formed by the half of the grating still uncovered. Thus if we cover each half of the pupil in turn we shall see the defect in the halo only when that half of the grating in which the defect is situated is uncovered. In the case we are discussing, it was observed that the defect could be seen when the right-hand side of the eye was uncovered but not when it was covered. It is clear therefore that the defect is in the top right-hand quadrant of the grating. In this way I have found no difficulty in locating on the grating the position of any irregularity which gives rise to an outstanding ray or marked distortion in the lenticular halo of either of my eyes. This result is very important, not for its practical value in locating the position of a defect, but because it proves conclusively that the rays in the lenticular halo are formed by irregularities in the spacing of the fibres in the crystalline lens.

**Size of the Lenticular Halo.**—The size of a halo can only be expressed in angular measure. If there is a small source of light (say a hole with a lamp behind) on an extensive vertical screen at the height of the eye, the halo always appears to be on the screen. It is then a simple matter to mark the position on the screen where any part of the halo appears to be situated. Let us in this way mark the positions of the end of the horizontal radius of any coloured ring of the halo and measure its distance from the centre, say $x$ cm. If at the same time we measure the distance of the eye from the screen and find it $y$ cm., then the ratio $x/y$ is sin $\theta$, in which $\theta$ is the angle subtended at the eye by the radius of the ring measured. It is this angle $\theta$ which is usually given as the " size " of the rings of a halo or corona, for it is constant and also independent of the distance of the source of light. There are several practical ways of measuring $\theta$; the method I used is described in detail in the Appendix.

**Physics of an Optical Grating.**—We have seen in the paragraphs dealing with the optics of a circular grating that, although the lines on a circular grating are not strictly parallel, the number involved in producing the spectrum on any radius of the halo is so small that we may consider the lines parallel and of constant thickness. Thus the laws of a normal rectangular grating can be applied to the lenticular circular grating. The fundamental equation of a grating is:

$$\sin \theta = \lambda / e \quad \ldots \ldots \ldots \quad (1)$$

in which $\theta$ is the deviation from the direct path produced by the grating on light of wavelength $\lambda$ (it is therefore in our case the angle subtended at the eye by the radius of the ring in the halo formed by light of wavelength $\lambda$),

and $e$ is the distance between the centres of adjacent grating spaces, *i.e.*, the width of the fibres.

As sin $\theta = x/y$, we have only to measure $x$ and $y$ as described for any one of the coloured rings in the halo to find the value of $\theta$. We can then by the application of Equation (1) find the value of $e$.

**Results of Measurements of** $\theta$.—I can detect no difference in the size of the haloes in my two eyes, and it is distinctly easier to make measurements using both eyes. The measurements shown in Table I, unless otherwise

TABLE I

MEASUREMENT OF LENTICULAR HALO

| 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|
| Radius Measured | $\frac{x}{y}$ sin $\theta$ | Angular Radius $\theta$ (degrees) | Wavelength $\lambda$ (mm.) | $e$ (mm.) |
| | | | $\times 10^{-5}$ | $\times 10^{-4}$ |
| Outer limit of Red ... ... ... | 0·068 | 3·9 | 70 | 97 |
| Orange-Yellow ... ... ... ... | 0·057 | 3·3 | 59 | 97 |
| Yellow-Green ... ... ... ... | 0·051 | 2·9 | 55 | 93 mean 94 |
| Green-Blue ... ... ... ... | 0·046 | 2·6 | 49 | 94 |
| Inner limit of Violet ... ... ... | 0·036 | 1·9 | 40 | 90 |

stated, were made using both eyes simultaneously. In measuring the rings, it is easier and more accurate to measure where the light changes from one colour to the next, say from yellow to green, than to measure the centre of each colour separately. In column 3 of Table I is given the value of the angular radius, θ, for each of the five positions on the halo specified in column 1, and column 4 contains the corresponding wavelengths. In column 5 are given values of *e* derived from θ and λ by Equation (1). Theoretically each measurement should have given the same value for *e*: considering that the limits of the inner violet and the outer red are not definite, the measurements are sufficiently in agreement for the mean value of *e* (0·0094 mm.) to be accepted as a near approximation. The actual width of the fibres from these measurements will be considered in the next paragraph. For comparison with other measurements it is convenient to know the mean angular radii for each coloured ring; this is given in Table II based on the measurements in Table I.

TABLE II
RADII OF COLOURED RINGS OF LENTICULAR HALO

| Colour | Radius θ of middle of ring (degrees) | sin θ | Wavelength λ (mm.) |
|---|---|---|---|
| | | | $\times 10^{-5}$ |
| Red ... ... ... ... | 3·7 | 0·064 | 68 |
| Orange ... ... ... ... | 3·4 | 0·059 | 63 |
| Yellow ... ... ... ... | 3·1 | 0·054 | 57 |
| Green ... ... ... ... | 2·8 | 0·049 | 52 |
| Blue ... ... ... ... | 2·5 | 0·044 | 47 |
| Violet ... ... ... ... | 2·2 | 0·038 | 40 |

**Size and Position of Fibres.**—Equation (1) assumes that the wave front is parallel to the plane of the grating where the two meet; in other words, the incident light on entering the grating forms part of a " parallel beam." This would be true if the grating were on the surface of the cornea, but it is situated on or in the crystalline lens, the equatorial plane of which is between 5 and 6 mm. behind the cornea. The incident light strikes the cornea as a parallel beam, but the cornea acts as the first surface of a compound lens, in consequence of which the parallel beam is changed into a converging beam. It is this converging beam which strikes the grating formed by the fibres of the crystalline lens. Druault (1923, p. 490; 1950, p. 340) has calculated the effect of this and shown that if *e* is the apparent grating space obtained by using Equation (1), the true value of *e* would be $e/1{\cdot}14$ if the active fibres were on the front surface of the crystalline lens, or $e/1{\cdot}32$ if they were on the posterior surface. As we do not know exactly where the active fibres are situated, he takes the mean of these two values and divides *e* obtained from Equation (1) by 1·23 to obtain the true width of the fibres. The factors 1·14, 1·23, and 1·32 are called by Druault the " coefficient of position " at the anterior, equatorial, and posterior surfaces of the crystalline lens.

Applying 1·23 as the coefficient of position appropriate to the fibres of the crystalline lens to the value of *e* found from equation (1), namely 0·0094 mm., we find the true value of the grating space to be $0{\cdot}0094/1{\cdot}23 = 0{\cdot}0076$ mm. We have taken the grating space to be the width of the fibres, hence in round figures, and that is all we are justified in using, the " width of the fibres " is approximately $8\mu$. Salzmann (1912, p. 172) gives the width of the fibres by dissection "perpendicular to the length and parallel to the surface" as $8$–$12\mu$.

In our discussion we have assumed that the fibres which cause the halo are confined to the outer zone of the lens and that there is no diffraction in the central part of the lens. This assumption is necessary, for if the fibres continued radially towards the centre there would be such a large difference between the grating space at the centre and at the periphery that narrow coloured rings such as are observed could not be formed. A simple direct observation however shows that this assumption is correct. If I place a card with a pinhole in it as close as possible to the pupil of the eye when observing a halo, I find that when the pinhole is near the edge of the pupil a portion of the halo appears; but when the pinhole is over the centre of the eye no sign of the halo can be seen although the source of light is clearly visible. The explanation is obvious: the pinhole confines the light from the source to a narrow beam, little larger in cross-section than the pinhole itself. When the pinhole is near the edge of the pupil the whole of this narrow beam passes through a small area of the grating, such as *G* in Fig. 3, and only the small sector of the halo corresponding to *G* can be seen. When the pinhole is over the centre of the pupil the absence of any portion of the halo indicates that the fibres do not produce diffraction there. With elaborate apparatus it might be possible by this method to mark out exactly how near to the centre the fibres cause diffraction; but there is a much simpler method which will serve our purpose.

A hole was pierced in each of three pieces of card having diameters of 2, 3, and 4 mm. respectively. Each card in succession was then held over the eye, with the hole as nearly over the centre of the pupil as possible, while a small source of light two or three metres away was viewed through the hole. The following results were observed:

(*a*) when the 2-mm. hole was used the source of light could always be seen without a halo,
(*b*) with the 3-mm. hole the card could not be held centrally for any length of time without the halo appearing faintly,
(*c*) with the 4-mm. hole the halo was always visible.

In short, a beam which is less than 3 mm. in diameter before entering the pupil can pass through the clear part of the lens without touching the grating, while a beam greater than 3 mm. in diameter before entering the pupil cannot pass through the clear space without passing through some portion of the grating also.

If it were not for the curved cornea between the hole and the grating we could have said at once that the diameter of the clear part of the crystalline lens is 3 mm.; but the beam which is parallel when it passes through the hole is converging after passing the cornea, hence its cross section is less on passing through the crystalline lens than when it passes through the hole. Using Druault's "coefficient of position," the diameter of the clear part of the crystalline lens would be $3/1 \cdot 23 = 2 \cdot 4$ mm. These values however cannot be exact and almost certainly vary from person to person. It is sufficient for all practical purposes to say that the diameter of the clear space within the grating in my eye is approximately 2·5 mm., *i.e.* the optically active fibres extend to within 1·25 mm. of the centre of my crystalline lens. As the diameter of the pupil varies from approximately 3 mm. in daylight to 6 mm. in artificial light, the width of the grating exposed in my eye varies from less than 0·25 mm. to more than 2 mm. according to the light.

**Variations in the Size of the Halo from Time to Time**

I commenced systematic observations on the lenticular halo on February 10, 1950. I cannot remember how bright the rings appeared when I first saw them, but they were obviously sufficiently striking for me to take them seriously, otherwise I should not have consulted a specialist. I can, however, remember that I had no difficulty in making measurements on them and I am not conscious of any change in the brightness of the haloes since I began to keep them under observation. When glaucoma had been diagnosed, but before the operation, I underwent a course of pilocarpine drops, which were introduced into the eyes three times a day. On each application of the drops the intensity of the haloes was much reduced and this was taken to confirm the diagnosis of glaucoma. When, however, the haloes were still visible after the operation it was realized that this temporary reduction in the intensity of the halo had been due to the reduction in the amount of light entering the eye owing to the contraction of the pupil caused by the drops. In 4 or 5 hours after the application of the drops the pupils had returned to their normal size and the haloes had regained their usual brightness.

I have measured the radius of the red ring (middle of the orange and red rings) very many times since February, 1950, and especially during the 20 days before the operation, when the pilocarpine drops were being applied daily and I have never found a measurable variation in their size, not even when they were almost invisible after the application of the drops. This is what would be expected if the rings are due to the lens fibres; for these are permanent structures in the eye and their size is not likely to change, except for the slow change due to normal growth.

**Tests for diagnosing the Lenticular Halo**

I propose to close this account of the lenticular halo by describing the tests which have been proposed for differentiating lenticular haloes from other coloured rings seen around the lights; not so much for their practical use, but as illustrating in a striking way the chief characteristics of this halo as described above.

(*1*) *Druault's Test.*—This was described in 1898 ; a detailed account will not be given here as it is readily accessible, and having now been superseded is of only academic interest.

(*2*) *Emsley-Fincham Test.*—This was described in 1922; it is essentially the same as Druault's test, but in a greatly improved form. A screen with a slit about a millimetre wide is passed across the eye; the resulting changes in the appearance of the haloes are striking, and are spread out over the whole traverse of the slit across the pupil. In Fig. 5, which is based on Fig. 3, only the portion of the

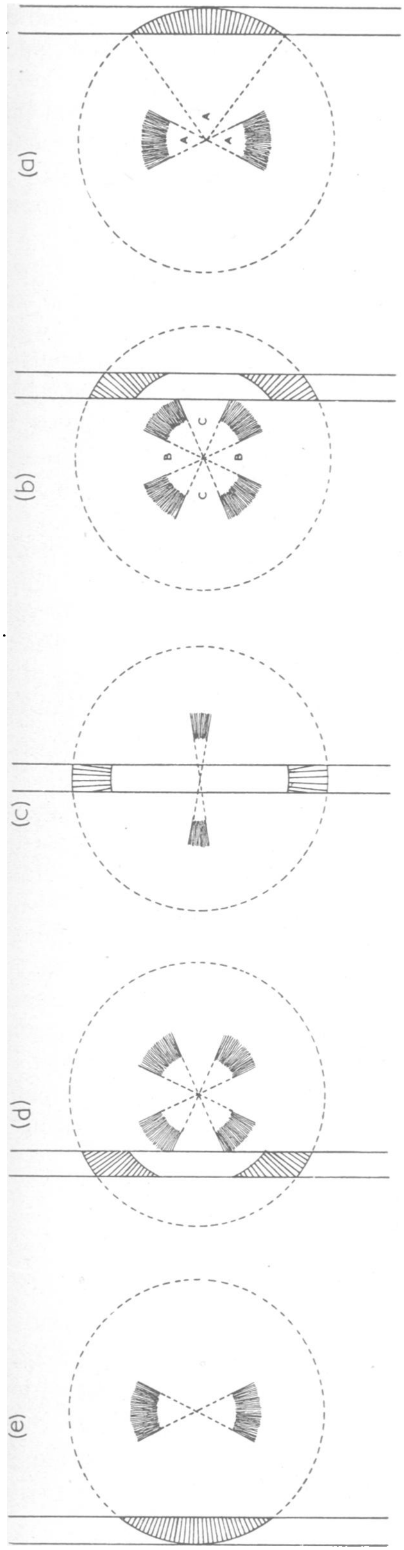



FIG. 5.—Appearances in Emsley-Fincham Test.

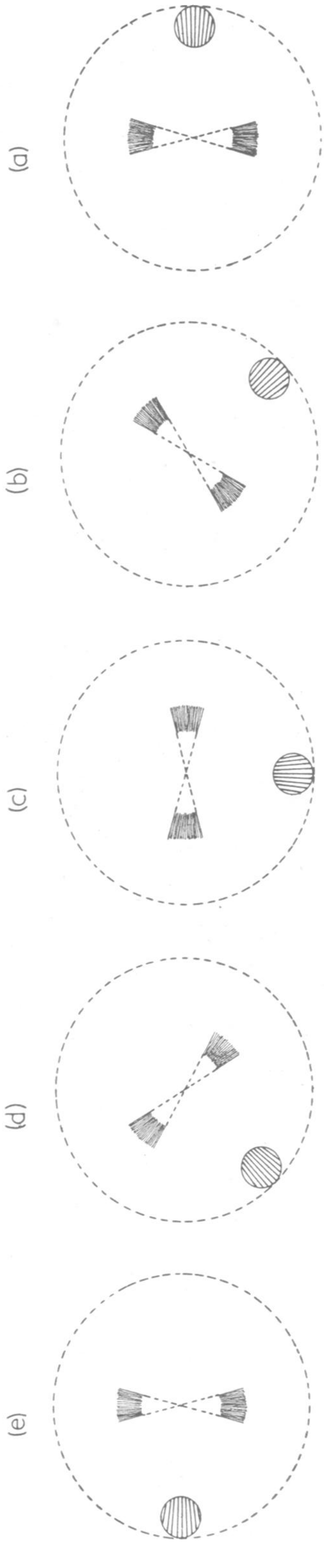



FIG. 6.—Appearances in modified version of Emsley-Fincham Test.

grating exposed to the incident light in each position of the slit is shown, and the diffraction pattern produced on the retina by that portion is shown in the middle of each of the five diagrams (*a–e*). The screen is travelling from right to left.

In Fig. 5(*a*), the following edge of the slit has just reached the right-hand edge of the pupil, so exposing a strip of grating on the extreme right. The diffraction produces two segments of the halo at opposite ends of the vertical diameter.

As the slit moves to the left, these segments extend and each one splits up into two, forming the cross shown in 5(*b*).

With continued motion of the slit to the left the breaks in the upper and lower segments, B and B, widen, while the gap between them, C and C, contracts, until the slit is exactly central when the arms of the cross meet as shown in 5(*c*), where the pattern again consists of two segments at opposite ends of a diameter, but this time a horizontal diameter.

As the slit continues to the left, the process is continued: the segments widen and then split to form a cross, 5(*d*); the arms of the cross approach one another and meet again to form one segment above and one below the central light, 5(*e*), repeating the pattern with which we started.

The whole effect is very striking, the formation of the cross and the movement of its arms can be seen when the halo is very faint. In fact it is the movement of the arms which catches the eye and the exact way in which the halo appears, splits up and disappears is of no importance in the test. By placing the slit over the centre of the eye and giving it slight movements to right and left, the arms of the cross appear to wave and there is nothing corresponding at all to this effect with any source of diffraction other than a circular grating.

(*3*) *Modification of Emsley-Fincham Test*.—A similar effect is obtained by using a hole instead of a slit in the screen. The hole should be large so as not to cut down the light too much, a hole 2 mm. in diameter is satisfactory. As this hole cannot illuminate more than a small section of the grating at any time, the complete halo can never be seen whatever may be the position of the hole over the pupil. Instead, one sees two segments of the halo, at opposite ends of a diameter (Fig. 6, p. 463). If the hole is now moved irregularly over the pupil, the two coloured spots will appear to dance and to chase one another around the light. With a little practice the hole can be moved in a circle around the circumference of the pupil when the coloured spots will rotate together in a kind of catherine wheel around the light at the centre (Fig. 6*a–e*). If a patient after a little trial can produce this effect it is certain that the coloured rings he sees is a lenticular halo.

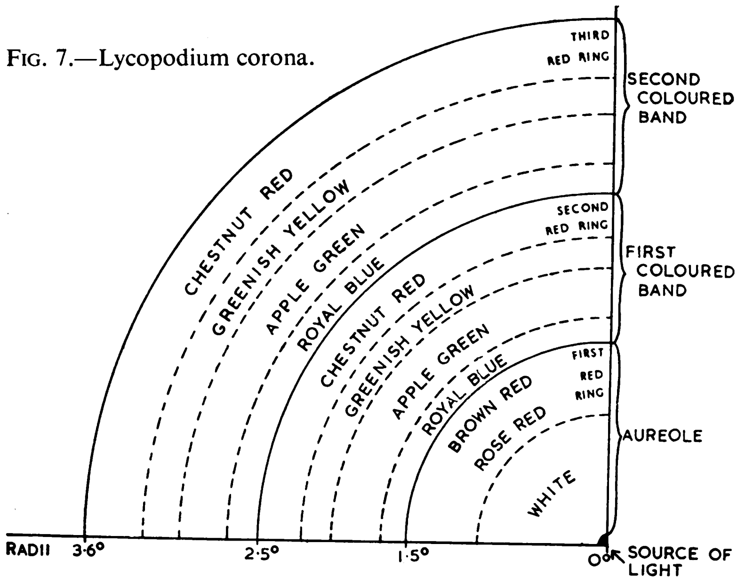
## CHAPTER II

## CORONA

**Coronas due to Particles.**—The most convenient method of studying these coronas is to distribute a thin layer of lycopodium powder between two circular pieces of glass, which fit the eye like a monocle, and observe a distant source of light through the disc thus formed. Lycopodium powder consists of nearly spherical spores which are all of practically the same size, the diameter being about 0·009 mm. (9$\mu$). When a distant, small. but bright, source of white light is viewed through such a disc, a brilliant corona will be seen. This is shown diagrammatically in Fig. 7. The corona consists of two parts (*a*) the aureole, and (*b*) the coloured bands; these must be described separately.

*The Aureole.*—The aureole is a bright disc of light, white at the centre and coloured towards the border. It is brightest near the centre and if the particles are very numerous blends into the source itself. The aureole decreases in brightness and tends to lose its whiteness as the distance from the centre increases: at about half-way across a tinge of yellow appears which becomes more and more red as the distance increases until the aureole ends in a broad, brown-red ring surrounded by a narrow dark ring. Thus the aureole is a bright disc of light, white near the centre, with a strongly coloured red border which forms the "first red ring" of the corona.

FIG. 7.—Lycopodium corona.




*The Coloured Bands.*—Surrounding the aureole with its red border is a series of coloured bands extending with decreasing brightness to a distance depending on the intensity of the source of light. Each band consists of a series of coloured rings, the colours (proceeding outwards) being blue, green, yellow, and red. This is the order of the colours in the spectrum, but these are not spectrum colours but "subtraction colours," for they result from subtracting spectrum colours from white light. The first ring is blue because yellow and red have been subtracted, the second green because red and blue have been subtracted, and so on to the final red ring from which the blue and green have been subtracted; they are the colours seen in soap bubbles and the pools of oil left on wet roads by motor cars; they are quite different from the pure spectrum colours of the lenticular halo. It will be noticed that the aureole and each of the coloured bands ends in a red ring. These red rings have a sharp junction with the dark blue ring of the following band which makes them good marks for measurement, and they have generally been used for this purpose since Fraunhofer first measured their radii in 1820 (Fraunhofer, 1823).

**Measurement of the Size of the Particles forming the Corona.**—The mathematical treatment of the formation of the corona has only been worked out for monochromatic light. With monochromatic light the corona consists of the aureole, surrounded by a number of bright rings with dark rings between them. The aureole itself is the first bright ring and therefore the first dark ring is the boundary of the aureole; bright and dark rings then follow in succession.

Formulae have been given relating the angle subtended at the eye by the radii of the rings, the diameter of the particles, and the wavelength of the monochromatic light. For the dark rings the formula is:

$$\sin \theta_n = \frac{n + 0{\cdot}22\lambda}{d} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

in which $n$ is the number of the dark ring ($n=1$ for the dark ring bounding the aureole);
$\lambda$ is the wavelength of the monochromatic light used;
$d$ is the diameter of the particles in mm.;
$\theta_n$ is the angle subtended by the radii of the $n^{\text{th}}$ dark ring.

It will be seen that, as we know $\lambda$ and $n$ and can measure $\theta$ (see Appendix), Equation (2) allows us to determine $d$. Although Equation (2) is strictly true only for monochromatic light, it has been found experimentally that when white light is used the dark rings which border the successive " red rings " may be considered to be the dark rings of white light; then Equation (2) holds if $\lambda$, " the wavelength of white light", is taken to be 0·000571 mm. Applying this method to the lycopodium corona, 0·029 mm. was found for the diameter of the particles, which is to be compared with 0·021–0·030 mm. found by direct measurement.

**Intensity of Light in the Corona.**—The mathematical discussion of the corona also leads to expressions for the intensity of the light in the different parts of the corona, but again for monochromatic light only. The formulae show that the intensity of the light (of all wavelengths), is greatest in the centre of the aureole near to the source of light; from this high intensity as one proceeds from the centre outwards the intensity decreases, slowly at first and then very rapidly to zero at the limit of the aureole; the intensity then rises to the maximum of the first ring and then there is a series of maxima with rings of no light (minima) between them. The ratio of the light from maximum to maximum is the same for all wavelengths, so that Table III applies to all wavelengths. From this it will be seen how much brighter the aureole is than the coloured rings. Yet it is possible to see four or five coloured bands with a good lycopodium disc and a bright light.

These intensities are the theoretical intensities for monochromatic light; now the brightness of colour is not the same thing as the intensity of light, therefore we are not justified in adding the intensities of several monochromatic lights to obtain the brightness of the mixture. We have however found that treating white light as monochromatic light of wavelength 0·000571 mm. gave useful results in determining the size of the particles forming the corona; we shall, therefore, in the absence of other means,

TABLE III

INTENSITY OF LIGHT IN A CORONA DUE TO PARTICLES

| Zone | Intensity |
|---|---|
| At centre of aureole ... ... ... ... ... ... ... ... | 1,000 |
| One-quarter across aureole ... ... ... ... ... ... ... | 800 |
| Half-way across aureole ... ... ... ... ... ... ... | 360 |
| Three-quarters across aureole ... ... ... ... ... ... ... | 80 |
| At circumference of aureole ... ... ... ... ... ... ... | 0 |
| At brightest part of first coloured band ... ... ... ... ... | 17 |
| At brightest part of second coloured band ... ... ... ... ... | 4 |
| At brightest part of third coloured band ... ... ... ... ... | 2 |

apply the same method to the problem of brightness. Hence we may expect that the ratios of the intensities given for monochromatic light in Table III will apply, approximately at least, to the brightness of the coloured bands when white light is used.

**Corona Seen.**—When I first saw coloured rings around street lights I had no doubt that I was seeing a corona similar to the one I have just described and which I had studied many years previously from the meteorological point of view. I was however, puzzled, because the rings I saw varied in several particulars from a true corona. In the first place, the central disc of white light was distinctly less bright in all parts than the coloured band surrounding it, while the aureole of the corona near the centre is more than fifty times brighter than the first coloured band. In the second place there was no red border to the white disc, the first coloured ring being distinctly violet. It was suggested to me that the rings I saw were due to the lenticular grating and not to particles in the eye; the application of the Emsley and Fincham test immediately proved this to be the case and I commenced the investigation of the lenticular halo described in Chapter I.

One morning in January, 1951, I looked out of the window while it was still dark and the street lamps were still alight, and then I saw around the nearest street lamp not the halo with which I had by then become very familiar, but a corona with a brilliant aureole and two conspicuous red rings. There could be no doubt I was at last seeing a real corona due to particles. The corona disappeared before I had time to make any measurements and was replaced by the lenticular halo in its usual form. I did not see a repetition of the corona for nearly a year, and then in November, 1951, I recognized it again, this time around the flame of a match. On both occasions I saw it early in the morning within a few minutes of waking. I therefore decided to look for it each morning immediately after waking and saw it on nine of the next twenty mornings but not at any other time of the day. I was now quite sure that I was seeing a true corona due to particles, something quite different from the halo which I can see at all times of the day and night. It was then November and therefore dark when I woke up each morning; so I fixed up in my study, next door to my bedroom, a convenient point source of light and the necessary apparatus for measuring the radii of the rings seen around it.

**Method used in Observations of the Corona.**—The following procedure was developed after a few days of experience. I was generally asleep when the alarm woke me at 6·48 a.m., and I immediately went into the study. This took one or two minutes during which I did not use my eyes more than was necessary to see my way about—I kept them closed most of the time. On arriving in the study I switched on the room light, then after a rapid look round to see that the apparatus was in order I switched it off again, turned on the experimental source of light, and stood in front of it to make the observations planned for that morning.

**Results of Observations.**—I rediscovered the morning corona on November 7, 1951, and observations were made on nearly every subsequent morning until March 25, 1952, when the increasing morning light (I had no completely dark room) put an end to them.

**The Liquid Glare.**—On first looking at the bright spot of light, within one or two minutes of waking, it was generally seen to be distorted by a film of moisture over the eye. This film was practically always present, sometimes more and sometimes less; its presence could be recognized by bright and dark areas with bright outlines in the field of view, just as one sees in the shadow of a sheet of glass on which a little water has been spilt. I call this effect " liquid glare." I have no reason to believe that the moisture in my eyes was excessive, there was no " weeping " and no deposits in the corners of the eyes; it was the normal moisture which accumulates under the eye-lids during sleep.

Unless the moisture was unusually pronounced, the normal lenticular halo could always be seen through the liquid glare for the first few minutes of observation; but there was no sign of any corona. During 5 months of daily observations there was only one morning on which a corona was present when I first looked at the source of light and on that morning the eye was inflamed by a stye. Normally it takes between 2 and 5 minutes from waking for a corona to appear. The importance of this interval will be discussed later.

If while continually watching the background around the central bright light—frequently covering first one eye then the other with the hollow of the hand in order to compare the development in the two eyes—a corona did not develop, the liquid glare slowly disappeared and the lenticular halo became clearer until it had regained its normal appearance. The observation was then over for that morning, for if the corona did not appear within 5 or 6 minutes of waking it was not seen that day.

**Development.**—If the corona is going to develop, the background within the lenticular halo becomes brighter and the outer red ring of the halo appears to become stronger and broader. This however is not a change in the halo, but the first sign of the formation of the aureole of the corona, the bright centre and red border of which cover the halo and swamp it. A green band then begins to appear outside the red border of the aureole. As the green band gets brighter, the second red ring appears beyond it, and finally we have a trace of green light beyond the second red ring. I have never seen the third red ring with certainty; but I have thought I got glimpses of it, no doubt if my light had been stronger I should have seen a third red ring.

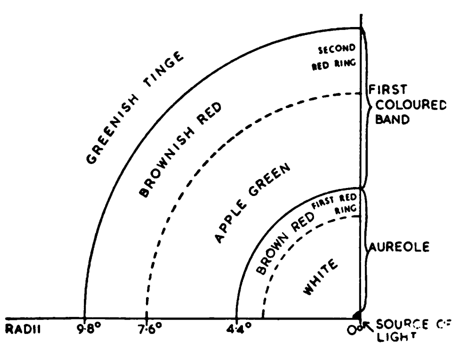



FIG. 8.—Descartes corona.

The fully developed corona which I see consists of a bright central disc surrounded by three coloured rings, the inner and outer being brownish-red and the one between apple-green. The corona is shown diagrammatically in Fig. 8.

**Disappearance.**—The corona does not remain visible for many minutes and has generally disappeared 15 minutes after waking. The disappearance is not sudden: the first sign that the corona has started to weaken is that I can see the halo through the corona; then the rings of the corona grow fainter and the halo by contrast clearer and sharper.

It has been stated in the literature that coronas disappear on blinking or on rubbing the eye. On twenty occasions when a corona was clearly visible I made tests to find the effect of blinking, rubbing, and washing the eye with distilled water or saline solution in an eye bath. There could be no possible doubt that neither blinking nor rubbing removed the corona: in fact, blinking appeared to accelerate its appearance, and although rubbing reduced the brightness of the corona at first, it soon recovered. On the other hand, washing the eye with distilled water or a saline solution removed the corona immediately. These experiments leave little doubt that the particles causing the corona are not within the eye, but on the surface of the cornea.

**Frequency with which Coronas were seen.**—I never saw a corona except in the morning within a few minutes of waking from sleep. They occurred in either eye, in both eyes simultaneously, or in neither. They occurred with large variations in intensity from day to day, from slight tinges of colour through which the lenticular halo could still be seen, to a brilliance which caused me one morning to enter in my notes "on using both eyes simultaneously the corona was glorious, there is no other word for it." (The bare filament of a 40-watt lamp seen through a 4-mm. diameter hole was used in this observation.) In order to record these variations I adopted a rough scale of intensity from 0 to 4 which was entirely subjective, and therefore cannot be used quantitatively for comparing individual observations, but which served a qualitative purpose.

Observations were made on 140 mornings and the results are shown graphically in Fig. 9. In this diagram the intensity of the corona, according to the scale mentioned above, is shown by a dot, to the left of the zero line for the left eye, and to the right of it for the right eye; a cross on the zero line indicates that there was no corona in either eye, and a circle that no observation was made that day.

Coronas were seen in one or both eyes on 61 per cent. of the morning observations, but they were very irregularly distributed. In December there was a sequence of 11 days during which coronas were not seen in either eye, while in March there was a

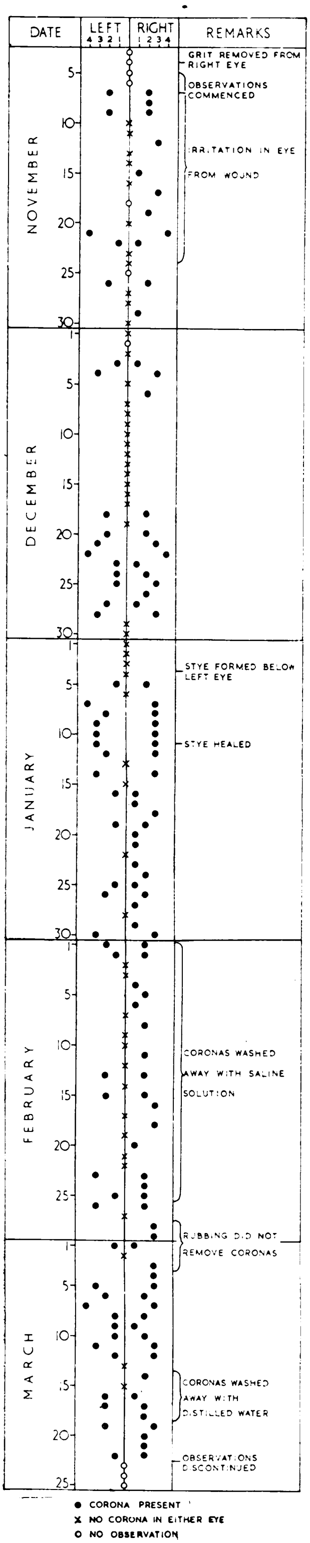



FIG. 9.—Frequency of Descartes coronas.

sequence of 10 days with coronas visible every day. On the other hand there was a period of 18 days (February 6–23) during which a corona appeared in one or both eyes on almost alternate days and no sequence with or without coronas lasted for more than 2 days.

Taking the two eyes separately: in 39 per cent. of the observations there was no corona in either eye; of the remaining 61 per cent. there was a corona in the right eye in every case, but in the left eye in only 36 per cent. Thus there were coronas in the right eye without one in the left eye in 25 per cent. of the observations; but there was not a single case in which a corona appeared in the left eye without one in the right eye. Because coronas appeared in the right eye nearly twice as often as in the left eye it must not be concluded that the coronas in the two eyes were independent of each other, for there was a high degree of correlation between the intensities in the two eyes when coronas appeared in both simultaneously, as will be clearly seen if Fig. 9 is examined in detail. The significance of these statistical results will be considered later, in the meantime they are collected together in Table IV.

TABLE IV

FREQUENCY WITH WHICH CORONAS WERE SEEN

| Site | Number | Percentage |
|---|---|---|
| Neither eye ... ... ... ... ... ... | 54 | 39 |
| Right and left eyes simultaneously ... ... ... | 51 | 36 |
| Right eye only ... ... ... ... ... ... | 35 | 25 |
| Left eye only ... ... ... ... ... ... | 0 | 0 |
| Total mornings with corona ... ... ... ... | 86 | 61 |
| Total mornings without corona ... ... ... | 54 | 39 |
| Grand Total ... ... ... ... ... ... | 140 | 100 |

**Colours of the Corona.**—The typical corona which I observe is represented in Fig. 8. It consists, as already stated, of a white aureole with a broad red border followed by a broader green ring and then by another red ring. This, at first sight appears to differ from the corona produced by lycopodium powder (Fig. 7), the aureole of which is surrounded by a sequence of coloured bands in each of which blue, green, yellow, and red rings can be recognized in accordance with the theoretical explanation of coronas formed by particles. There is, however, no real difference. The theoretical discussion deals with a point source of light and equal particles. When the particles are of the same average size, but with an appreciable range of individual sizes, the coloured rings are broadened and overlapping takes place. Consider now the first coloured band in Fig. 7. The intensity of the rings in this band is three times as great as the intensity of those in the next band, therefore we may neglect the latter, and consider that the corona ends with the second red ring. When the red ring is broadened there is no mixing on the outer edge, therefore the ring will be broadened and remain red; on the other hand, the other rings will overlap, the yellow with the green and the green with the blue. All these mixtures have a green hue and therefore this part of the coloured band will lose its clear cut rings of yellow, green, and blue and appear as a green band, slightly blue on the inside and blending into the red on the outside.

These small differences of tint are hardly perceptible and the appearance is as described: an apple-green band between two red bands surrounding the white centre of the aureole. From this we learn that the particles forming the coronas are much less uniform in size than the spores of lycopodium.

**Size of the Corona.**—From what has been said it is clear that the red rings in the observed corona, Fig. 8, correspond with the red rings in the theoretical corona, Fig. 7. We can therefore determine the size of the particles on the cornea which cause the coronas by measuring the outer radii of the two red rings.

It was not easy to make this measurement, for the coronas are so transient that by the time one was sure that the corona had developed sufficiently for a measurement to be made, there was very little time left for making the measurement. In all, I was able to make 83 separate measurements on 14 days, and from these it is possible to say that:

(*a*) the size of the rings was remarkably constant, the variations from day to day being well within the somewhat wide limits of observational error;
(*b*) there was no consistent change in the size during the measurements on any one occasion.

From (*a*) we can conclude that the average size of the particles was the same from day to day, and from (*b*) that they did not grow in size after appearing nor decrease in size before disappearing.

Table V, giving the dimensions of each ring of the corona, has been constructed from the means of all the observations.

TABLE V
RADII OF COLOURED RINGS OF CORONAS

| Ring or Band | Position of Measurement | sin θ | θ |
|---|---|---|---|
| First red ring ... ... | Inner edge (approx.)... ... ... | 0·057 | 3·3 |
| | Brightest part... ... ... ... | 0·071 | 4·1 |
| | Outer edge / Inner edge ... ... ... ... ... | 0·077 | 4·4 |
| Green band... ... ... | Middle ... ... ... ... | — | (6·0) |
| | Outer edge / Inner edge ... ... ... ... ... | 0·132 | 7·6 |
| Second red ring ... ... | Mean radius ... ... ... ... | 0·144 | 8·6 |
| | Boundary (approx.) ... ... ... | 0·170 | 9·8 |

We can now find the size of the particles responsible for the coronas by putting the values for sin θ for the two red rings from Table V in equation (2), and taking $\lambda = 0{\cdot}000571$ (the wavelength of white light).

$$\textit{First red ring,} \quad n = 1, \quad d = \frac{1{\cdot}22}{0{\cdot}077} \times 5{\cdot}71 \times 10^{-4} = 0{\cdot}0091 \text{ mm.}$$

$$\textit{Second red ring,} \quad n = 2, \quad d = \frac{2{\cdot}22}{0{\cdot}17} \times 5{\cdot}71 \times 10^{-4} = 0{\cdot}0074 \text{ mm.}$$

These two values for *d* should be the same; the measurements, however, were too consistent for the discrepancy to be due to observational error; it is much more likely to be due to the large spread in the size of the particles. In any case the difference is of little importance, and the mean of the two, 0·008 mm. (8$\mu$), cannot be far from the average diameter of the particles. For comparison we may note that the diameters of the lycopodium spores, cloud particles, and red blood corpuscles are 21 to 30$\mu$, 4 to 20$\mu$, and 7 to 8$\mu$ respectively, while the limit of unaided vision may be taken to be 50$\mu$.

**Rays.**—In common with other coronas due to particles, morning coronas, under certain conditions, take on a radial structure. The rays are well marked in the aureole and in the first red ring and can be seen to half-way across the green band. The difference between these rays and those of the lenticular halo is that the halo is composed entirely of rays which can be seen individually, while in the corona the rays appear to be superimposed upon the aureole and coloured rings, which otherwise are uniform. These rays will be further discussed in Chapter III.

## Nature of the Particles causing the Coronas

These morning coronas have long been recognized for what they are: the diffraction effect of particles within or upon the surface of the eye. But the problem of what the particles are is far from solved. I will give quotations going back for nearly a century in which suggestions are made on the nature of the particles.

(*a*) Les couronnes qu'on voit souvent, autour des chandelles, le matin en se levant, sont dues à des globules de sang injectés dans la conjonctive (*sic*) pendant le sommeil. Billet (1858).

(*b*) Il est sans doute produit par des globules de pus étalés à la surface de la cornée. Druault (1899, p. 13).

(*c*) For a period during the summer of 1921 one of the authors could see a halo each morning, due to mucus having formed on the cornea. Emsley and Fincham (1922, p. 271).

(*d*) Leucocytes or fatty particles on the cornea are probably responsible for the rings that sometimes occur with conjunctivitis. Priestley Smith (1924, p. 153).

Here we have five substances suggested as the origin of the corona: blood corpuscles, spheres of pus, mucus, leucocytes, and fatty particles. I propose to review my observations to see if they throw any light on this problem.

On November 4, 1951, 3 days before I saw the corona which led to the long series of morning observations, I had considerable pain in my right eye due to the presence of a piece of grit which had to be removed by a doctor. For the next 20 days there was considerable irritation in the eye and during this period I saw a corona in one or both eyes on nine of the mornings (see Fig. 9). As I had only once before seen the corona, a year previously, I naturally associated its continued appearance with the wound in the eye caused by the grit. At this period I had not yet commenced to measure the size of the corona; but it was subsequently found that its size indicated that the diameter of the particles was 8$\mu$. As this is the size of red blood corpuscles the association of the corona with the wound receives some support, although there was no visible sign of blood. The difficulty of this explanation is that the wound was in the right eye only, yet on four of the nine occasions during this period on which a corona was seen in the right eye, it was seen equally bright in the left eye, in which there could have been no blood from the wound.

After the irritation had disappeared, there was a period of 40 days (Nov. 24–Dec. 3) in which, so far as I could tell, the eyes were perfectly normal. At first there were occasional appearances of the corona, on five mornings out of thirteen; then there was a period of eleven mornings without a corona, followed by eleven mornings only one of which was without a corona (in the latter period the coronas were more frequent and on the whole brighter than during the period after the grit had been removed); another period of six mornings without a corona brought the 40 days of normal eye conditions to an end. Here we see periods of bright coronas and of no coronas with nothing to give a clue to anything which might account for them.

On the morning of January 4, 1952, a stye was seen to be developing on the lower lid of the left eye. There was no corona on the morning of January 4 but poor coronas appeared in both eyes on January 5: the stye was not yet affecting the eye. Finding no corona on January 6, I examined the left eye and found a region of red discoloration below it. The stye had a yellow head, and after growing more and more irritable all day it broke in the evening and discharged a quantity of pus which was carefully removed with a swab. On waking on January 7, there was some resistance to raising the eyelids apparently due to moisture in both eyes. In a minute or two after starting the usual morning observation, coronas appeared in both eyes, that in the left eye somewhat the brighter. On January 8 the flow of pus from the stye ceased, but the left eye continued inflamed until January 11, during which period there was rather more moisture than usual in both eyes, but no deposit of solids in the corners. From January 7 to 11 there were bright coronas in both eyes. It is possible that pus could have got into the left eye during the 3 days, January 6, 7, and 8, when there was discharge from the stye, but it is difficult to see how it could have got into the right eye.

Before leaving the period affected by the stye, it should be pointed out that measurements of the coronas gave no further information about the nature of the particles. Good measurements of the size of the rings were made on 4 days between December 22 and 29, all more than 6 days before the stye appeared, and on 3 days, January 7, 8, and 9, during the discharge of the pus. The results were identical, showing particles of $8\mu$ diameter: thus the size of the particles was the same in periods when there was not even the possibility of pus being present and periods when pus was present. This does not point to pus being the active agent in producing the corona.

The irritation due to the stye ceased on January 11 and afterwards to the end of the observations on March 28 there were mornings with coronas and mornings without; but no evidence was offered as to the possible origin of the particles.

The observations just described do not throw much light on the nature of the particles causing the corona. Blood possibly might have been responsible in the period after the wound, November 4–24, and pus in the period January 4–11; but then there would remain the difficulty that in each case coronas appeared in both eyes when only one could have been contaminated. This also leaves unexplained all those cases in which equally bright coronas were present in periods when the eye appeared to be normal and when there was certainly no discharge of blood or pus.

At one time I thought that the coronas were associated with the amount of moisture in the eye, but there were so many occasions with large amounts of liquid glare without coronas appearing that moisture cannot be the direct cause of the coronas. On the other hand normal moisture was associated with the periods following the wound and the stye; now these were periods of considerable direct irritation in one eye and sympathetic irritation in the other. Is it not possible that the coronas are associated with the irritation and not directly with the blood, pus or moisture ?

On January 21 I made the following note:

> These traces of coronas in the right eye may be associated with a slight prickling under the lid of this eye as though there were some grit between the lid and the eye. I only notice this when I wake up in the night.

During the remaining 3 months of the observations there are several references in my notes to this " prickling," and I summed up my thoughts on the matter as follows:

> The prickling in my right eye has continued since I first noticed it. It is clearly noticeable when I wake in the night and on first waking in the morning. I do not remember noticing it in the daytime. Once or twice I have felt a slight prick in the left eye; but in any case it is much less in the left than in the right. I have not been able to detect any correlation between the prickling and the appearance of the corona.

Combining these remarks on the prickling with those on the effect of irritation, I think a case can be made out for the prime cause of the corona being irritation in the eye, this would explain the coronas following the grit and the stye and also the greater frequency of coronas in the right eye than in the left eye. But this does not explain what the actual particles are and why they require several minutes to become active when the eyes open after several hours sleep. These are questions, however, for the ophthalmologist, rather than for the physicist.

### Descartes' Description of a Corona

In his *Discours de la Méthode* (1637), Descartes described, with an illustration, a corona which he observed around the flame of a candle. The original was written in Latin; but I am translating from Victor Cousin's modern French version published in Paris in 1824.

> Finally, the cause of the rings which are sometimes seen around lamps and candles should not be sought in the air, but in the eye which sees them. Last summer I had

an experience which illustrated this very clearly. It was during a night voyage on a ship; I was making astronomical observations, watching the sky with one eye while keeping the other closed with the hand on which I was supporting my head. I had been observing all the evening when someone brought a lighted candle to the place where I was sitting.

On opening both eyes I saw two coronas (Lat. *coronantes*) around the flame [Fig. 10] of which the colours were as bright as I have ever seen in a rainbow; A B, the larger,

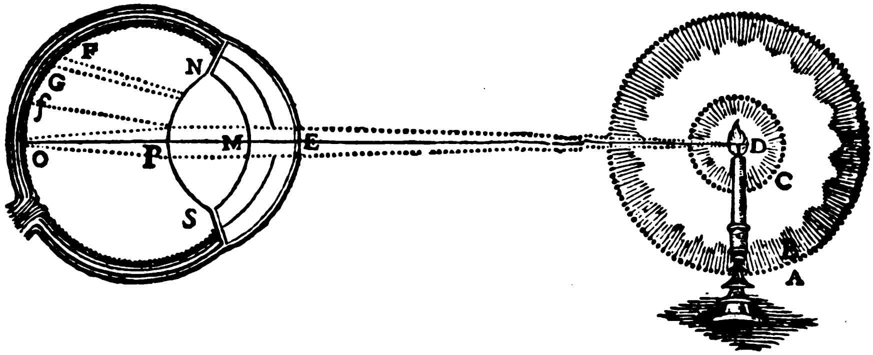



FIG. 10.—Descartes' diagram from "Oeuvres de Descartes" (1824), vol. 5, p. 292

was red towards A and blue towards B; C D, the smaller, was also red towards C, but towards D it was white and extended up to the flame. After that on closing the right eye I saw that the corona had disappeared; on the other hand on opening the right eye and closing the left they reappeared; this convinced me that the rings could be caused only by some disposition which my right eye had acquired while I had kept it closed.

There can be no doubt that Descartes had seen a corona similar to the corona we are discussing in this chapter. This comes out more clearly in the diagram than in the description. There can be no doubt to anyone who has seen the corona that the two shaded bands in Descartes' diagram are the two red bands. What Descartes calls the smaller corona, C D, is clearly the aureole with its red border. The description of his " larger corona " is not so satisfactory, for the expression " red towards A and blue towards B " is hard to interpret, and he gives no description of the colour of the clear ring between the two red rings; if we neglect " blue towards B " the rest of the description fits a corona consisting of a white aureole, and two red rings with a green ring between as shown in Fig. 8. It is very unlikely that Descartes made his drawing (or a sketch) while the aureole was still visible; it is much more likely he would draw it some time later from memory; if this is so it is surprising how nearly he has got the proportion between the radii of the rings correct as will be seen by comparing Descartes' corona with Fig. 8.

Descartes himself remarks:

> it is very common to those who have diseased eyes to see such coronas and they do not appear similar in all cases.

From this it is clear that coronas were well known in Descartes' time and probably they may have been mentioned in earlier writings, but there can be little doubt that Descartes was the first to give a description of any entopical diffraction phenomenon accompanied by an attempt to explain it in what we today would consider a strictly scientific manner. So far as I know ophthalmologists have no definite name for the corona described in this chapter, and I have felt the need for one in writing the account of my observations. I therefore suggest that the name "Descartes Corona" could usefully be adopted as the scientific name for the corona which was first described by Descartes in 1637.

## CHAPTER III

## THE CILIARY CORONA

In my general description, in Chapter I, of the coloured rings which I see around lights I mentioned (p. 453) a disc of white light in the space between the source of light and the coloured rings. This I said was not part of the halo, and I postponed further discussion of it, saying that it would be the subject of this chapter.

We now know why the light in question cannot be part of the halo; for the halo is the first order spectrum of an optical grating, and there is no light in the space between the image of the source of light and the spectrum formed by a grating. When I came to describe to my friends the rings I see around lights and asked them to describe what they saw, I soon found that they also saw a glow around the same lights, but without any surrounding coloured rings. On making enquiries from ophthalmologists I learnt that this glow around bright lights is well known and is seen by all normal eyes; it is called the "ciliary corona." When I enquired the cause the only reply I could get was that it was due to "scattering," which is hardly a satisfactory answer. We have now to see if we can find the nature and cause of the ciliary corona.

**Description of the Ciliary Corona.**—In Fig. 2 (p. 454) I attempt to depict the ciliary corona as I see it within my lenticular halo. It consists of a disc of white light which is brightest near to the centre and decreases in brightness as the distance from the centre increases. On first sight this disc appears to have no particular texture, but on closer study it is seen to consist of a large number of fine white lines radiating from the central source of light superimposed on a background of innumerable points of light. These are so small that they are difficult to see individually, but produce the appearance of a uniform white surface. The word "point" is used advisedly here in order to reserve the word "spot" for use later when discussing much larger points of light. We must now study the corona in greater detail, discussing first the bright points of light and then the rays.

**Points of Light in the Ciliary Corona.**—When a white source of light is viewed by the naked eye, the points of light appear at one moment to be in rapid and agitated motion and then they suddenly stop and remain as though fixed in position. So long as the head is held still and the eyes focused on some feature in the field of view the bright points appear stationary; but if the head moves or the eyes wander the points set themselves into rapid motion. It is difficult to describe this motion, for although there is no recognizable pattern it is not entirely irregular. The best description I can give is to liken it to a milling crowd of people, some moving in one direction and some in another; when viewed as a whole some portions of the crowd appear to have a general movement or surge in a definite direction, which direction is not long maintained, while other positions have surges in other directions. The bright points have a similar unco-ordinated motion; but occasionally the points in all parts of the corona move for a short time towards the centre and at other times away from the centre. Similarly radial motion can sometimes be seen in limited portions of the field. The only cases of regular motion which I have recognized take the form of circular waves originating at some particularly bright point on the source (probably points on the coiled filament of the lamp) and radiating outwards like the circular waves which spread over a sheet of water when a stick is moved backwards and forwards in the water near the bank. All these motions are most pronounced when one first looks at the light; for then it takes some time for the head and eyes to settle down. I have, however, failed to find any close relationship between any specified motion of head and eyes and the resulting movement of the points. When the points are in agitated motion the individual points appear to twinkle as well as to move; then, as the motion decreases, the twinkling also decreases, and when the motion has stopped entirely the brightness of the points remains constant.

When I examine the ciliary corona through my reading spectacles (11-inch focus, which ordinarily I do not wear when making these observations), the rays and the small points of light disappear, and are replaced by a small number of bright white spots. These spots have similar motions to those of the bright points, they are stationary when the head and eyes are fixed and are in rapid movement and twinkle when head or eyes are not at rest; their movement is much more striking because owing to their brightness it is more easily followed. I shall have to return later to these bright points and spots in an attempt to find their origin. In the meantime, the distinction between the " points " seen with the naked eye and the " spots " seen when spectacles are used, should be noted; the former are small and difficult to see, while the latter stand out like stars on a dark background.

Turning now to the rays seen in the ciliary corona, these are nothing like so prominent as those of which the lenticular halo is composed. As seen round the street lamp, they are not very conspicuous against the background formed by the bright points of light. It is seldom that a single ray can be traced from the centre to the edge of the corona; they have more the appearance of the individual hairs in a tress of hair, they lie in the same general direction, but are not straightened under tension. It is difficult to describe the rays in any detail, for the whole effect is near the limit of vision; but when examining the points of light and the rays intently I have the feeling that the rays are produced by the alignment of the bright points; and there is some colour effect as though the rays were built up of very short spectra; but the individual spectra cannot be studied for the whole effect is so elusive. As already stated, when the corona is viewed through spectacles the rays and points of light completely disappear, and are replaced by bright spots; it is as though all the light in the aureole, normally consisting of bright points and rays, is collected together into relatively few bright spots.

When sodium light was used at the National Physical Laboratory a yellow ring was seen with a radius of 3·1°, which is obviously the sodium line in the circular spectrum forming the lenticular halo; we are not concerned with this ring at present as it is beyond the ciliary corona. Within the space surrounding the central source of yellow light, where the ciliary corona is normally situated, there were neither points nor rays as with white light, but a large number of bright spots of yellow light standing out sharply against a black background. The spots were most closely packed near the light, thinning out towards the edge of the disc. The spots were relatively large and bright, very similar to those seen with white light when spectacles are used and like them, sometimes stationary and sometimes in motion. When the intensity of the light was not great the whole cluster was well within the yellow ring of the halo. As the intensity of the source was increased the diameter of the cluster of spots became larger and reached the yellow ring of the halo, the position of which is of course not altered by the intensity of the light, and when the light had become very intense the boundary of the spots passed beyond the yellow ring and the brilliance of the whole phenomenon became too painful for prolonged viewing.

When mercury light was used there were two predominant rings in the halo, one green and the other blue, corresponding to the two main lines in the mercury spectrum. The phenomenon was similar to that for sodium light: there was a cluster of bright green and blue spots within the two rings of the halo, and the cluster expanded as the intensity of the source increased, finally passing beyond the two rings.

Exner (1877) showed that with white light the aureole of a corona due to uniform particles is a brilliant white disc, falling off in intensity from the centre and becoming red towards the border where its intensity becomes zero (see p. 465); if monochromatic light is substituted for the white light the whole aureole breaks up into a very large number of spots of monochromatic light which show up brilliantly against a black background.

This is exactly what occurs with the ciliary corona so that there can no longer be any doubt that the ciliary corona is the bright central portion (aureole) of a corona produced by particles of uniform size distributed at random somewhere in the substance of the eye.

A question which now arises is: why are there no coloured rings around the ciliary corona if it is the aureole of a corona ? The answer is clear: the intensity of the light in different parts of a corona due to particles is given in Table III, from which it will be seen that the intensity of the light in the first coloured band is only $1\frac{1}{2}$ per cent. of that near the source. As the ciliary corona, even near the source, is always faint compared with the intensity of the light in the source itself, the coloured band could not be seen unless the intensity of the source was so great that it would be intolerable to look at with the naked eye. This also accounts for another characteristic of the ciliary corona which at first sight seems strange. In all other coronas in which the coloured bands are seen, the size of the aureole and rings is independent of the intensity of the light; the size of the ciliary corona however expands and contracts as the intensity of the source increases and decreases. The explanation follows from what has just been said. As no light can ever be seen beyond the aureole, there must be a point on the radius of the aureole, where the light ceases to be visible, and this point moves outwards as the intensity of the light in source increases. Thus the apparent size of the ciliary corona is a function of the intensity of the source of light.

**Location of Particles in the Eye.**—Having now concluded that the ciliary corona is due to particles in the eye, we must consider where they are situated. Several ophthalmologists with whom I have discussed my observations have remarked that the wandering of the spots of light suggests the aqueous rather than the vitreous humour as the location of the particles. This is because they are under the impression that the spots are images of the particles; this, however, is a misapprehension, for a foreign particle in the eye cannot be " seen." The spots are certainly not images of particles moving freely about. In order to explain the formation of the spots of light in the aureole when monochromatic light is used, Exner suggested that, with a random distribution of diffracting particles, the light waves from the particles will not be evenly distributed over the retina, but will combine at certain places to produce amplitudes larger than average and so to give rise to the sensation of spots of light. Accepting this explanation and assuming no change in the position of the particles, there would be a change in the distribution of the light on the retina if there were any change in the path of the light waves within the eye. For example, any small muscular change affecting the crystalline lens would produce a redistribution of the light reaching the retina, involving a change in the position on the retina of the localities with large amplitudes. In this way an apparent movement of the visual spots would occur without any movement of the diffracting particles. This is not the place to develop this idea; but it illustrates the nature of the physical and physiological problems involved. With the amount of information available it is not possible to locate the position of the particles within the eye, and this question must remain over for further work.

**Size of Particles causing Ciliary Corona.**—If we could determine the radius of the ciliary corona we could calculate the size of the particles causing it. We have however seen that we cannot ever measure the radius of the aureole, as what is seen does not extend even so far as the limit of the aureole. We can, however, say that the true radius of the aureole is greater than the largest radius measured. In my experiments at the National Physical Laboratory the intensity of the sodium light source was increased to the limit of tolerance when the spots were already beyond 4° from the centre. This obviously gives a lower limit to the size of the aureole. Putting $n=1$, $\theta=4°$, and $\lambda=\cdot00059$ in Equation (2) (p. 466), we find the diameter of the particles, $d$, to be 0·01 mm. As the aureole was certainly larger than 4°, $d$ must have been smaller than 0·01 mm., thus we finally arrive at this statement:

The diameter of the particles causing the ciliary corona cannot be larger than 0·01 mm. ($10\mu$) although they may be much smaller.

## Rays seen in Ciliary Corona

We must now turn our attention to the streaks or rays of white light which are seen in the ciliary corona. Similar rays are associated with other coronas produced by particles, and have been the subject of occasional studies by physicists. The most recent of these studies that I can find is that of de Haas (1918), who studied the development of the diffraction pattern as he increased the number of small holes, one by one, in a screen mounted to show the diffraction produced by the holes. His paper is not entirely convincing, and the problem of the formation of the rays is still far from solved. As the observations I made on the rays of the ciliary and other coronas are I believe new and provide further information on the rays, I propose to describe them in some detail, so that they may be used by physicists in further work on this subject.

**Radial Structure of Coronas produced by Particles.**—In the following paragraphs I propose to discuss the rays seen in coronas produced by the random distribution of spherical or nearly spherical particles, chiefly the ciliary corona, but also those produced by lycopodium powder, blood smears, etc., the physical properties of which are known. Unless specially mentioned, the rays of which the lenticular halo is composed are not included, as these are produced by inequalities of the grating and are not directly diffraction effects.

Very soon after commencing my study of the ciliary corona, I noticed that the rays were much finer and brighter when the source of light was the filament of a clear electric bulb seen through a small hole, than when a pearl bulb was seen through the same hole. Some time later I noticed when using the pearl bulb that the rays became relatively brighter and more pronounced the further I removed away from the light. At first I did not connect these two observations. One day on observing the corona through a lycopodium disc, when I was using a pearl bulb behind a large hole as the source of light, I noticed that rays which were quite clear when the source was viewed from a distance of 5 or 6 ft. entirely disappeared when I approached to within 3 ft. of the source. At all distances nearer than this the corona consisted of aureole and coloured rings without any sign of rays either within the aureole or crossing the rings. A few rough tests showed that the distance from the source at which the rays disappeared as one approached the source was greater for large sources and smaller for small sources. Further and more accurate tests showed that, when a circular uniformly illuminated source of diameter $d$ was viewed through a lycopodium disc from a distance $l$, the rays always appeared when $d/l$ had the same value: in other words, when the diameter of the source subtended a certain angle at the eye, the rays appeared; with a larger angle there were no rays, with a smaller angle rays were always visible. I call this angle, $\varphi$, the "ray-formation angle," and the distance, $l$, between the eye and the source, the "ray-formation distance"; so that $d/l=\sin\varphi$.

With lycopodium, the ray-formation distance for a given source can be determined with little difficulty, for the change from rays to no rays is relatively sharp. Table VI contains the ray-formation angle for lycopodium

TABLE VI
RAY-FORMATION ANGLE FOR LYCOPODIUM

| Diameter of source (mm.) ... ... | 2 | 3 | 4 | 6 | 8 | Mean |
|---|---|---|---|---|---|---|
| Ray-formation angle (min.) ... ... | 23 | 24 | 22 | 23 | 23 | 23 |

powder for five uniformly illuminated circular sources of different sizes.

The next step was to make similar observations on the ciliary corona, for if the effect is the same it removes any lingering doubt as to whether the ciliary corona is a diffraction or a mere scattering effect. The first observation made with the naked eye showed at once that qualitatively the effect is the same; but it was not easy to get consistent numerical values. In the first place the rays are much less bright with the naked eye than with the lycopodium disc, and therefore it is much more difficult to fix the ray-formation distance. In the second place I found that looking at the bright light gave after-images which were troublesome. The measurements soon revealed a difference between the two eyes so that each eye had to be treated separately. After considerable experimental observation, a method was evolved which got over these difficulties and produced repeatable values.

The source of light was the surface of a 40-watt pearl electric bulb placed immediately behind a hole of the required size in a black screen. The number of sizes of the source to be examined was reduced to three, namely diameters of 2, 3, and 4 mm. The observations were made in a completely dark room. After fixing the source to be measured I waited in the dark until the eyes were dark-adapted. I then placed an eye-shade over the right eye and determined the ray-formation distance for the left eye; then I removed the eye-shade to the left eye and made an observation with the right eye. After waiting until any after-image had completely disappeared from both eyes, the observation was repeated with another size of source. I continued this procedure until I had made three observations with each eye on each of the three sources, this took about half an hour. If by this time the eyes were getting tired I took a few minutes rest before repeating the whole series. The complete series, consisting of six observations with each eye on each of three sizes of source, *i.e.*, 36 observations in all, took between 60 and 90 minutes. Table VII reproduces a set of observations

TABLE VII

RAYS IN CILIARY CORONA

Individual values of $l$ and mean values of $\phi$ in one set of observations, December 28, 1951

| Diameter of Source ($d$) (mm.) ... ... | | 2 | | 3 | | 4 | | Mean |
|---|---|---|---|---|---|---|---|---|
| Eye ... ... ... ... ... ... | | Left | Right | Left | Right | Left | Right | |
| 1 | Individual Observations of $l$ (cm.) | 30 | 38 | 51 | 71 | 71 | 89 | — |
| 2 | | 33 | 30 | 46 | 61 | 66 | 79 | — |
| 3 | | 36 | 36 | 43 | 71 | 69 | 86 | — |
| 4 | | 28 | 43 | 46 | 64 | 79 | 79 | — |
| 5 | | 23 | 41 | 51 | 63 | 66 | 76 | — |
| 6 | | 43 | 36 | 53 | 61 | 74 | 86 | — |
| 7 | Mean $l$ (cm.)... ... ... ... | 32 | 37 | 48 | 65 | 71 | 83 | — |
| 8 | Sin $\phi = d/l$ ... ... ... ... | ·0062 | ·0054 | ·0063 | ·0046 | ·0056 | ·0048 | — |
| 9 | Mean $\phi$ (min.) ... ... ... | 21 | 19 | 22 | 16 | 19 | 17 | — |
| 10 | Ratio $\phi_L/\phi_R$ ... ... ... | 1·11 | | 1·38 | | 1·12 | | 120 |
| 11 | Mean $\frac{1}{2}(\phi_L+\phi_R)$ (min.) ... ... | 20 | | 19 | | 18 | | ·19 |

made in this way, in which separate columns are given for the left and right eye separately; the order of the observations was as shown in the Table, starting at the left-hand end of the first line and ending at the right-hand end of line 6. The whole set of 36 observations in this case took 65 minutes.

Lines 1–6 give the individual values of the ray-formation distance ($l$) for each eye, and three sources of different sizes. Considering the difficulty of the observations, the individual numbers in the separate columns do not show an unduly large scatter. Line 9 shows that the mean values of the ray-formation angles for the two eyes are somewhat different; but line 10 shows that the ratio between the eyes is practically constant. Line 11 shows that the ray formation angle, using the mean for the two eyes, is practically independent of the size of the source. This however is only the result from one day's observation. Observations by this method were repeated on three successive days and are summarized in Table VIII; they proved to be so consistent that I did not feel it necessary to take further observations.

TABLE VIII

RAYS IN CILIARY CORONA

Mean Values of Ray-formation Angle, $\phi$

| Diameter of Source (mm.) ... ... | 2 | | 3 | | 4 | | Mean | |
|---|---|---|---|---|---|---|---|---|
| Eye ... ... ... ... ... | Left | Right | Left | Right | Left | Right | Left | Right |
| Mean $\phi$ (min.) ... ... ... | 21 | 18 | 21 | 16 | 19 | 17 | 20 | 17 |
| Ratio $\phi_L/\phi_R$ ... ... ... | 1·17 | | 1·31 | | 1·12 | | 1·20 | |
| Mean $\phi$ (min.) ... ... ... | 20 | | 19 | | 18 | | 19 | |

From this Table we see that for the ciliary corona in my eyes the angle subtended by the diameter of the source at the eye must be smaller than 19′ for rays to be seen; some slight difference is shown in the two eyes—left eye 20′, right 17′—this difference is real; but its significance will remain unknown until we know more about the origin and physics of the rays.

I have not had the opportunity of testing other eyes in the same complete manner; but a few tests on three of my friends, both of lycopodium and ciliary coronas, showed that they had no difficulty in determining the ray-formation distance and their measurements were numerically comparable with mine.

In addition to the lycopodium and ciliary coronas I made similar measurements on the Descartes corona (seen on waking) and on that produced by a smear of blood on a glass slip. The results for these four coronas are collected in Table IX (opposite). The diameters of the particles causing the coronas are given in the last column.

It will be seen that the ray-formation angle, $\varphi$, is in each case found to be independent of the diameter of the source; there is, however, a considerable variation for the different coronas in the size of this angle, from 19′ for the ciliary corona to 37′ for the blood corona. One's first idea is that $\varphi$ would

TABLE IX

RAYS IN FOUR DIFFERENT TYPES OF CORONA

Value of $\phi$

| Diameter of Source (mm.) | ... | 2 | 3 | 4 | Mean | Diameter of Particles |
|---|---|---|---|---|---|---|
| Type of Corona | Lycopodium ... | 23′ | 24′ | 22′ | 23′ | 30μ |
| | Descartes ... ... | 29′ | 28′ | 26′ | 28′ | 9μ |
| | Blood smear ... | 43′ | 35′ | 32′ | 37′ | 7μ |
| | Ciliary ... ... | 20′ | 19′ | 18′ | 19′ | <10μ |

depend in some way on the size of the particles; but the diameter of the particles forming the corona (last column), appear to have no relationship with the mean values of $\varphi$ in the previous column. Considerable light is thrown on this aspect by the observations made on the Descartes corona. On six mornings I was able to measure the ray-formation angle for this corona as well as the radii of the rings, thus obtaining simultaneous values of the ray-formation angle and the size of the particles (Table X).

TABLE X

RAYS IN DESCARTES' CORONAS

Mean values for ray-formation angle, $\phi$, on six mornings

| Date | No. of Measurements | Diameter of Source (mm.) | | | | Diameter of Particles |
|---|---|---|---|---|---|---|
| | | 2 | 3 | 4 | Mean | |
| December 23 ... | 4 | 35′ | 35′ | 34′ | 35′ | 9μ |
| December 26 ... | 2 | 17′ | 19′ | 18′ | 18′ | 9μ |
| December 29 ... | 2 | 27′ | 20′ | 21′ | 23′ | 9μ |
| January 7 ... ... | 3 | 27′ | 27′ | 25′ | 26′ | 9μ |
| January 10 ... ... | 3 | 38′ | 41′ | 36′ | 38′ | 9μ |
| January 12 ... ... | 3 | 30′ | 24′ | 22′ | 25′ | 9μ |
| Mean ... ... | ... | 29′ | 28′ | 26′ | 28′ | 9μ |

The first thing to notice in Table X is that the ray-formation angle varied largely from day to day (column 6); that these variations are real is shown by the fact that the same angle was found for all three sources on any one morning (columns 3, 4 and 5). If these variations from day to day had been due to variations in the size of the particles this would have been shown by variations in the radii of the rings (column 7), which depend on the size of the particles. But in all six cases no measurable difference was found, showing that the size of the particles remained constant. Thus we can definitely say that the size of the ray-formation angle is not determined by the size of the particles causing the corona.

All the rays we have discussed so far are associated with coronas produced by particles distributed at random between the source of light and the retina. Rays are however a feature of the lenticular halo, and these also disappear if one approaches close enough to the source. The ray-formation angle, $\varphi$, for the halo is 39′, which is to be compared with the angle for the coronas given in Table IX. It is larger than the angle for any of the coronas, but only slightly larger than that for the blood corona, namely 37′. There can be little doubt that de Haas is right in attributing the rays in the coronas to secondary diffraction effects between the diffracting particles; there can be still less doubt that the rays in the halo are due to the irregular distribution of the fibres which form the lenticular grating. Why the rays produced by these two different physical effects should both have a constant ray-formation angle, is another problem for physical research.

**Origin of Bright Streamers seen radiating from Intense Sources of White Light.**—If one looks at the reflection of the sun in a sheet of glass or in the surface of a puddle it can be viewed for a short time without discomfort. The sun will then be seen as a clear cut disc of light with a perfectly sharp edge, there will be no rays radiating out from it. The same is true of the moon, the disc is clear without rays of any kind. We now know the reason for this, the angle subtended at the eye by both sun and moon is 30′ while the ray-formation angle for the ciliary corona is 19′, thus both sun and moon are too large when seen from the earth to produce rays. If now we examine the image of the sun in a convex or concave mirror, the bowl of a silver spoon will do very well, we see it surrounded by innumerable brilliant rays streaming out to a distance of several degrees from the centre. The mirror has reduced the apparent diameter of the sun to such an extent that the angle it subtends at the eye is well below 19′, and the ciliary corona now consists almost entirely of rays. That it is the reduction in the apparent size of the sun, and not the reflection from the mirror, which has induced the ray-formation, can be seen by breaking the original sheet of glass into small pieces. Each piece is now too small to reflect the whole disc of the sun, but can only reflect a portion, and if this portion subtends at the eye an angle of less than 19′, the rays will be seen. The same effect is seen when one catches glimpses of the sun between the leaves as one walks in a wood. The portions of the sun glimpsed in this way are accompanied by numerous rays. In this case no reflection is involved.

At the National Physical Laboratory I was shown an intense source of electric light the area of which had been reduced to a mere pin-point. It was the centre of a most brilliant disc composed entirely of the finest streamers of white light.

The rays or streamers seen round brilliant small sources of light are therefore a diffraction effect, produced by the same particles within the eye as produce the glow seen round every bright source of light (the ciliary corona); they are not shown when the point of light is photographed in a camera.

## Summary

The author describes in detail three ocular diffraction phenomena and discusses the physics of their formation based on observations made on his own eyes.

(*a*) It is confirmed that the coloured rings sometimes called the lenticular halo form a circular spectrum produced by the radial fibres of the crystalline lens, which become sufficiently uniform in size and regular in arrangement near to the periphery of the lens to act as an optical grating. The angular

radius of the yellow ring ($\lambda = 0.00057$ mm.) is found to be 3.1° and the radii of the other coloured rings to be in linear proportion to their wavelength. The optical measurements give 8 $\mu$ as the width of the fibres which are optically active to within 1 or 1.5 mm. of the centre of the lens. Methods of differentiating the lenticular halo from other coloured rings are discussed.

(*b*) Observations of the corona first described by Descartes in 1637 and usually seen within a few minutes of waking were made each morning during 5 months. This corona consists of a bright white central aureole surrounded by three broad coloured rings: the first red, the second green, and the third red; traces of further red and green rings could sometimes be seen. The central radii of the first three rings are 4.1°, 6.0°, and 8.6° respectively; from this it is deduced that the corona is caused by particles with diameter of 8 $\mu$. Experiments show that these particles are present on the anterior surface of the cornea; they cannot be removed by blinking or rubbing but are immediately dissolved in a bath of distilled water or saline solution. The nature of the particles is discussed without any conclusion being reached. The name "Descartes corona" is suggested for these rings.

(*c*) The glow seen around bright lights is called the ciliary corona because it is frequently seen to be composed of bright fibre-like rays of light. It is shown that this corona is also a diffraction effect, the rays becoming visible when the source of light subtends an angle of at least 19′, *i.e.*, when the distance of the light from the observer is greater than 180 times its diameter. The diffraction is due to particles of uniform size (diameter less than 10 $\mu$) somewhere in the body of the eye. The nature of these particles and their exact location in the eye are as yet undetermined.

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# APPENDIX

## METHOD OF MEASURING THE COLOURED RINGS

The following has been found a convenient method of measuring the radii of the coloured rings.

A wooden box of 18″ × 12″ × 6″ is used; the vertical front 18″ × 12″ is made of thin brass sheet, hinged at the top with the edges turned over the sides and bottom to form a light-tight door to the box. In the centre of the brass plate is a circular hole ($\frac{1}{8}''$ in diameter) and in the horizontal line through this hole there are sixteen holes ($\frac{1}{10}''$ in diameter) spaced at intervals of an inch, eight on each side of the central hole and numbered 1 to 8 from the centre outwards; the fifth hole on each side has two additional holes, one above and one below, to facilitate counting the holes in the dark. There is a similar series of small holes on the vertical line through the central hole extending five inches above and below the central hole; Fig. 11 shows the arrangement of the holes. The brass plate forming the front of the box is painted black.

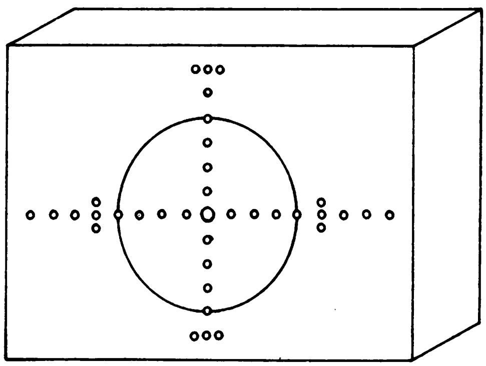

FIG. 11.—Box for measuring rings.

Behind the central hole, within the box and nearly touching the front plate, is a 100-watt pearl electric bulb which is mounted on a brass rod screwed into the bottom of the box so that the lamp may be raised and lowered to bring the brightest part immediately behind the hole. Thus the central hole is brilliantly illuminated and forms the "bright source of light" under observation. A sufficient thickness of thin card is pasted on the back of the brass plate within the box over the smaller holes to cut down the light from the interior of the box to the minimum necessary for the small holes to be just visible in the dark.

Between the central hole and each of the small holes to the left and right short pieces of wire are soldered and bent to form hooks to either of which the end of an inch tape-measure can be attached.

Before making a measurement the height of the box is adjusted so that the central spot is at the level of the observer's eye, and the tape-measure is attached to the hook on the same side of the central spot as the eye to be tested—say the left-hand side. When the observer stands in front of the box he sees the central bright spot surrounded by the coloured rings which contract and expand as he moves towards or away from the box. He takes the tape measure in his left hand and approaches the box until the ring he is measuring is seen between the central spot and the first small spot. He then moves backwards until the ring coincides with spot No. 1 on one of the rows of spots and checks this by seeing that the corresponding spots on the other three rows are also on the ring. He then raises the tape-measure, holding it lightly between thumb and first finger some distance short of the eye, and brings it into contact with the corner of the eye by sliding the thumb and finger along the tape. The room light is then turned up and the position of the grip on the tape-measure read off and recorded.

The observation is then continued, using other spots in turn, until sufficient measurements have been made to give the accuracy required.

If it is required to make observations with different sized sources it is easy to have the central hole enlarged and a frame soldered around it into which brass slides, each with a different sized hole can be slipped.